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FREDYN Simulations of HALIFAX for Determining Helicopter Securing Loads

Doug Perrault

Kevin McTaggart

Defence R&D Canada – Atlantic

Technical Memorandum

DRDC Atlantic TM 2004-043

March 2004

Canada

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Abstract

In support of procurement of new maritime helicopters, DRDC Atlantic was tasked to simulate motions of the HALIFAX class in seaways. The data produced will aid in the determination of helicopter securing loads, which are highly dependent upon the motions of the ship. The present work reports a systematic series of simulations modelling a HALIFAX class frigate with nominally steady speed and heading (course-keeping) in a variety of seaway conditions. This memorandum provides the explanation of the procedure used as well as the key results. A companion report (DRDC TM 2004-044) contains tabulated results from the simulations.

Résumé

En appui à l'acquisition des nouveaux hélicoptères maritimes, RDDC Atlantique a reçu le mandat de simuler les mouvements d'un navire de la classe HALIFAX en mer. Les données produites permettront d'aider à déterminer des charges d'arrimage sécuritaires pour les hélicoptères, qui sont extrêmement dépendantes des mouvements des navires. Le présent travail présente la série systématique de simulations utilisées pour modéliser une frégate de la classe Halifax croisant à une vitesse régulière et selon une orientation (conservation de cap) en présence de diverses conditions de voies navigables. Le mémoire présente une explication de la procédure utilisée de même que des principaux points. Un rapport d'accompagnement (RDDC TM 2004-043) comprend une description des simulations présentée sous forme de tableau.

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Executive summary

Introduction

When onboard ship, maritime helicopters are secured to the deck using either a landing probe or a combination of the landing probe and chains. The loads required for securing the helicopter depend on the ship's motions. To assist with specification of design loads for the securing devices, DRDC Atlantic was tasked to compute motions of the HALIFAX class frigate at the locations where the helicopter would be secured. The simulations cover a range of sea conditions, ship speeds and headings.

Principal Results

A systematic series of simulations was carried out for HALIFAX in the operational light condition, at various speeds and headings, and with a specific variation of seaway parameters for both open ocean and coastal waters. The operational light loading condition for HALIFAX was selected as a likely conservative case because motions tend to become greater as displacement decreases. The principal results are files of time series data for each simulation run, as well as statistical analyses of the motion parameters.

Significance of Results

The data provide numerical values for the key parameters (roll angle, pitch angle, accelerations of the ship at two specific securing points) for determining the design loads for securing devices. This memorandum provides the explanation of the procedure used and plots of the key results. A companion report (DRDC TM 2004-044) contains tabulated results from the simulations. Care is required in using the data provided: Since motions are dependent on the displacement and mass distribution of the ship, significant changes from the operational light condition specified herein will influence the validity of the data.

Future Plans

The data presented in this report will likely be used for developing design loads for the Maritime Helicopter Project. The data could also be used for a wide variety of other purposes, such as to investigate the feasibility of specific deck operations under various combinations of seaway, ship's speed and relative heading.

Doug Perrault, Kevin McTaggart; 2004; FREDYN Simulations of HALIFAX for Determining Helicopter Securing Loads; DRDC Atlantic TM 2004-043; Defence R&D Canada – Atlantic.

Sommaire

Introduction

Les hélicoptères maritimes embarqués sont arrimés au pont au moyen d'un sabot d'atterrissage ou d'une combinaison de ce dernier et de chaînes. Les charges requises pour arrimer l'hélicoptère dépendent des mouvements du navire. Pour aider à la spécification des charges d'échantillonnage des dispositifs d'ancrage, RDDC Atlantique a été mandatée de calculer les mouvements d'une frégate de la classe HALIFAX à l'endroit où l'hélicoptère est arrimé. Les simulations couvrent toute une gamme de conditions maritimes, de vitesse de navire et de caps.

Principaux Résultats

Une série systématique de simulations a été effectuée pour la classe HALIFAX en conditions opérationnelles à l'état lège, selon divers vitesses et caps, ainsi qu'avec une variation spécifique des paramètres de navigabilité en haute mer et en eaux côtières. Les conditions opérationnelles à l'état lège pour la classe HALIFAX ont été sélectionnées en retenant des valeurs vraisemblablement conservatrices car les mouvements tendent à devenir plus importants lorsque que le déplacement diminue. Les principaux résultats sont des fichiers de séries de données chronologiques pour chaque essai de simulation, de même que des analyses statistiques des paramètres de mouvement.

Importance des Résultats

Les données fournissent des valeurs numériques des paramètres clés (angle de roulis, angle de tangage, accélérations du navire à deux points d'attaches spécifiques) pour déterminer les charges d'échantillonnage des dispositifs d'ancrage. Le mémoire fournit une explication de la procédure utilisée de même que des principaux points et résultats. Un rapport d'accompagnement (RDDC TM 2004-044) présente sous forme de tableau les résultats des simulations. La prudence est de mise avec les données fournies : les mouvements étant dépendants du déplacement et de la distribution de la masse du navire, tout changement important des conditions opérationnelles à l'état lège spécifiées ici influencera la validité des données.

Plans Futurs

Les données présentées dans ce rapport seront vraisemblablement utilisées pour développer les charges d'échantillonnage pour le projet d'hélicoptère maritime. Ces données pourront également être utilisées à d'autres fins, notamment pour étudier la

faisabilité des opérations de pont spécifiques en présence de diverses combinaisons de navigabilité, de vitesse et de cap relatif de navire.

Doug Perrault, Kevin McTaggart; 2004; FREDYN Simulations of HALIFAX for Determining Helicopter Securing Loads; DRDC Atlantic TM 2004-043; Defence R&D Canada – Atlantic.

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1 Introduction

The Department of National Defence's Maritime Helicopter Project (MHP) is responsible for procurement of new ship-borne helicopters, including the full integration of the helicopter and on-board support systems with the ship. During operation in heavy seas, ship-borne helicopters are secured to the deck using either a landing probe or a combination of the landing probe and chains. The loads required for securing the helicopter are highly dependent upon the motions of the ship. To assist with specification of design loads, the Maritime Helicopter Project tasked DRDC Atlantic to compute motions of the HALIFAX class over a range of sea conditions, ship speeds and headings.

Previous studies provided some of the required data.

1.1 Course-keeping in High Sea States

In the first study [1], FREDYN version 7.7 was used to perform a series of simulations involving a parametric model of the HALIFAX class. The simulations included both course-keeping in high sea states and maneuvering in a variety of sea states. The course-keeping portion is particularly relevant to the present study. In that original study there were two categories of conditions:

1. Sea state 8 (significant wave height: $H_S = 11.5$ m and peak period: $T_P = 16.4$ s), where the HALIFAX was simulated at ship's speeds of 5, 10, and 15 knots, and at relative headings of 0° to 180° (in 30° increments) at each speed.
2. Ship-survivability limits ($H_S = 15.0$ m, $T_P = 18.0$ s) with ship's heading of 180°, and ship's speed of 5 knots. These conditions represent the survivability requirements of the HALIFAX class frigates, which must not be reduced by the presence of a helicopter properly secured in the hanger. As well, the helicopter must be able to survive and remain secured to the deck in these conditions.

The operational light loading condition for HALIFAX was selected as a likely conservative case because motions tend to become greater as displacement decreases. Several of the ship's parameters for the operational light loading condition[1] in the original study [1] are significantly different from those in the present study (see Table 1).

None of the simulations included the effects of wind. The seaways were built up from 20 component waves to form a unidirectional seaway.

[1]The operational light loading condition used herein is the best estimate of what that condition will be when the helicopters are put into service. The actual condition at that time will likely be somewhat different.

The simulation time step was $0.1\ \mathrm{s}$ (as requested by MHP) for all runs. The duration of each simulation was one hour, which is considered adequate for providing enough motion data for meaningful statistical analysis.

1.2 Course-keeping in 6 m Waves

Further simulations are reported in [2] using FREDYN version 8.2 with a parametric model of the HALIFAX class frigate in $6\ \mathrm{m}$ waves (significant wave height) having periods of $13.6\ \mathrm{s}$ and $8.9\ \mathrm{s}$. The focus of that study was oriented towards flight deck operations rather than securing loads, leading to the specification of H_S = $6\ \mathrm{m}$, which is considered to be the limit for flying operations from the HALIFAX class. The specified peak wave period of $13.6\ \mathrm{s}$ represents the most probable value for the North Atlantic given a significant wave height of $6\ \mathrm{m}$. Specified ship speeds of 10, 15, and 20 knots are realistic values for the specified sea state. Lower ship speeds are considered unlikely because of potential problems with course-keeping at low speed in a high sea state. Several of the ship's parameters for the operational light loading condition in this study are significantly different from both those in the original study [1] and those in the present study (see Table 1).

It is assumed that waves are collinear to the wind (mean wind speed of 28 knots), which is a reasonable assumption for higher sea states. Using the convention of 0° for head winds, headings of 0° to 90° were simulated (in 15° increments), and simulation results were categorized as to whether or not they were within the allowable relative wind speed envelope (see [2] for details).

Long-crested irregular seaways were simulated using linear superposition of 20 sinusoidal components. Bretschneider spectra were used to define sea states for all cases.

The simulation duration was specified to be 30 minutes, which was considered to be a representative operational duration. An analysis of the variability of maximum responses with seaway realization indicated that if maximum roll angles are well below the capsize regime, then the maximum response in a 30 minute simulation will not be very sensitive to seaway realization, therefore only a single seaway realization was used.

1.3 Course-keeping in a Variety of Seaways

It is also conceivable that helicopter securing loads could be greater when the ship is in a lesser seaway but at less than optimal speed and heading. In light of this, the MHP asked for a more comprehensive set of data to include other seaway conditions that affect the securing of helicopters in the hangar or on the flight deck

Table 1: *Main Particulars for HALIFAX Class Frigates, Operational Light Loading Condition for Previous Studies and Present Study*

	High Sea State [1]*	**6 m Waves** [2]†	**Current Study: Variable Seaways**†
Length, L (m)	124.5	124.5	124.5
Beam, B (m)	14.7	14.7	14.78
Midships draft, T_{mid} (m)	4.64	4.643	4.96
Trim by stern, t_s (m)	0.0	0.575	0.0
Displacement, $\triangle$ $(tonnes)$	4179	4316	4700
Longitudinal centre of gravity, $\overline{LCG}$, (m) aft of midships	6.44	—	2.8
Height of CG above waterline (m)	1.80	—	1.74
Vertical centre of gravity, $\overline{KG}$ (m)	—	6.70	6.70
Metacentric height, $\overline{GM}_{fluid}$ (m)	1.224	0.908	0.89
* No wind. † Wind included			

of a HALIFAX class frigate. The present work reports the systematic variation of seaway parameters for both open ocean and coastal waters using FREDYN version 8.2. For each seaway, simulations were conducted for a matrix of ship speeds and headings, where the ship's speed was varied from 0 to 30 kts in 5 kt increments, while the ship's heading was varied from 0° to 345° in 15° increments.

Each seaway was built up from 20 component waves to form a unidirectional seaway. Bretschneider spectra were used to simulate deep water seaways, and JONSWAP spectra were used to simulate littoral seaways.

For each wave height the corresponding mean wind speed (determined as a function of significant wave height) at 19.5 m elevation is assumed to be from the starboard beam regardless of wave direction.

1.4 Relationship of the Three Reports

The second report [2] is different in focus and approach than the original study [1] and the present investigation. Because of the differing conditions of both the ship parameters and, more significantly, the seaway configurations, all three reports clearly provide different and useful information; there is no overlapping information.

1.5 Outline of This Report

This report presents some of the resulting data from simulations of HALIFAX with nominally steady speed and heading (course-keeping) in each seaway. Section 2 gives a brief description of the program FREDYN used for the present simulations. The ship and environmental conditions are presented in section 3. Section 4 describes the results of the simulations, and section 5 presents final remarks.

A companion report [3] presents tabulated results from the simulations.

2 Description of FREDYN

The program FREDYN computes motions of a ship maneuvering in waves and wind. The Cooperative Research Navies (CRN) Dynamic Stability Project, of which DND is a participant, has sponsored the code development by Maritime Research Institute Netherlands (MARIN). FREDYN uses a nonlinear strip theory approach, which gives good results for large amplitude motions of slender vessels such as frigates. This study uses Version 8.2 of FREDYN, which is described in detail in proprietary documents [4], [5]. McTaggart and de Kat [6] give an overview of FREDYN in the open literature. This version of the code has compared favourably with data from sea trials aboard the HMCS NIPIGON[7]. FREDYN 8.2 was found to give good agreement in heave and pitch (within 10 %), and fair agreement in roll (overestimated by approximately 50 %). Because of the classified nature of many propulsion characteristics of the operational naval ship, some assumptions were made with respect to those propulsion characteristics.

FREDYN uses an earth-fixed axis system (x_e, y_e, z_e) and a ship-fixed axis system (x_g, y_g, z_g), as shown in Figure 1. The x_e-y_e plane lies in the still waterplane, with the z_e axis pointing downward. The ship-fixed system (x_g, y_g, z_g), which has its origin at the ship center of gravity, rotates and translates as the ship moves. When the ship is at rest in a calm water, the z_g axis points downward. Note that in the FREDYN output, these axes and all other parameters are represented by capital letters, as in Figure 1. Translations in position, as well as velocities and accelerations are positive in the direction of the axes. Rotations and rotational velocities and accelerations are positive when they are in accordance with the right-hand rule (with the right hand thumb pointing along the axis, the fingers curl in the direction of a positive rotation).

Table 2 gives some of the main FREDYN output parameters. Note that the output value for ZE, the vertical displacement of the ship CG, is given relative to its value when the ship is at rest in calm water. Table 3 gives some of the acceleration parameters also generated by FREDYN. Application of FREDYN output often requires

Table 2: *FREDYN Output Parameters*

Parameter	Units	Description
T	(s)	Time relative to beginning of simulation
ZETAG	(m)	Wave surface displacement at ship CG
ALFAY	(deg)	Beamwise component of wave slope at ship CG
XE	(m)	Displacement of ship CG along x_e axis
YE	(m)	Displacement of ship CG along y_e axis
ZE	(m)	Displacement of ship CG along z_e axis (relative to calm water value)
PHI	(deg)	Ship roll angle about x_e axis, positive starboard side down
THETA	(deg)	Ship pitch angle about y_e axis, positive bow up
PSI	(deg)	Ship yaw angle about z_e axis, positive bow to starboard (also represents ship heading relative to x_e)
PSI - PSI0	(deg)	Ship heading relative to initial heading, positive bow to starboard
UG	(m/s)	Speed of ship CG in direction x_g
VG	(m/s)	Speed of ship CG in direction y_g
WG	(m/s)	Speed of ship CG in direction z_g
P	(deg/s)	Roll velocity about x_g, positive starboard side down
Q	(deg/s)	Pitch velocity about y_g, positive bow up
R	(deg/s)	Yaw velocity about z_g, positive bow to starboard
DEL(1)	(deg)	Rudder angle, positive trailing edge to port

Table 3: *FREDYN Output Accelerations*

Parameter	Units	Description
XCOG	(m/s^2)	Acceleration of ship CG in direction x_g
YCOG	(m/s^2)	Acceleration of ship CG in direction y_g
ZCOG	(m/s^2)	Acceleration of ship CG in direction z_g
PDOT	(deg/s^2)	Roll acceleration about x_g, positive starboard side down
QDOT	(deg/s^2)	Pitch acceleration about y_g, positive bow up
RDOT	(deg/s^2)	Yaw acceleration about z_g, positive bow to starboard
X1	(m/s^2)	Acceleration of 1^{st} point on ship, parallel to x_g
Y1	(m/s^2)	Acceleration of 1^{st} point on ship, parallel to y_g
Z1	(m/s^2)	Acceleration of 1^{st} point on ship, parallel to z_g
X2	(m/s^2)	Acceleration of 2^{nd} point on ship, parallel to x_g
Y2	(m/s^2)	Acceleration of 2^{nd} point on ship, parallel to y_g
Z2	(m/s^2)	Acceleration of 2^{nd} point on ship, parallel to z_g

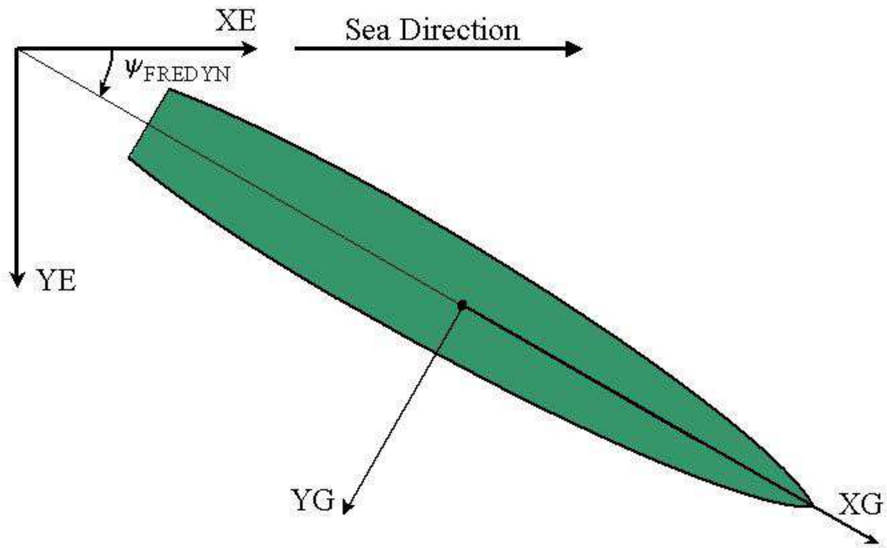

***Figure 1:** Plan View of FREDYN Axes (ZE and ZG axes point downward;)*

transformation of results from earth-fixed to ship-fixed axis systems. The output rotational parameters are based on the following sequence of rotations:

1. a yaw rotation ψ about the vertical z-axis (which is initially parallel to the z_e-axis),

2. a pitch rotation θ about y-axis of yawed coordinate system,

3. a roll rotation ϕ about the x-axis of yawed and pitched coordinate system.

Transformations of translational and angular velocity components are as follows:

$$\left\{ \begin{array}{c} \dot{x}_e \\ \dot{y}_e \\ \dot{z}_e \end{array} \right\} = [T_{3f}]^{-1} \left\{ \begin{array}{c} \dot{x}_g \\ \dot{y}_g \\ \dot{z}_g \end{array} \right\} \tag{1}$$

$$\left\{ \begin{array}{c} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{array} \right\} = [T_{3v}]^{-1} \left\{ \begin{array}{c} p \\ q \\ r \end{array} \right\} \tag{2}$$

where p, q, and r are the ship angular velocity components in the ship-fixed co-

ordinate system. The transformation matrices are:

$$[T_{3f}]^{-1} = \tag{3}$$
$$\begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\phi+\cos\psi\sin\theta\sin\phi & \sin\psi\sin\phi+\cos\psi\sin\theta\cos\phi \\ \sin\psi\cos\theta & \cos\psi\cos\phi+\sin\psi\sin\theta\sin\phi & -\cos\psi\sin\phi+\sin\psi\sin\theta\cos\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\phi\cos\theta \end{bmatrix}$$

$$[T_{3v}]^{-1} = \tag{4}$$
$$\begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta} \end{bmatrix}$$

3 Simulation Conditions

The conditions for the simulations were specified by the Maritime Helicopter Project. The operational light loading condition for HALIFAX (see Table 1) was selected as a likely conservative case because motions tend to become greater as displacement decreases.

Several seaway conditions were investigated in order to give a comprehensive set of data. Bretschneider spectra were used to simulate deep water seaways, and JONSWAP spectra (with a Gamma value of 2) were used to simulate littoral seaways. Tables 4 and 5 give the respective particulars of the specific seaways modelled. As can be seen in these tables, each sea state has two corresponding wave periods, each representing roughly a practical limit of wave period for that particular sea state. The selected wave periods represent the 5^{th} and 95^{th} percentiles, given the significant wave height. In all cases the significant wave height is the upper value for the associated sea state. The last two Bretschneider seaways (Sea State $>$ 8) are based on the HALIFAX performance requirements for survivability without serious damage to mission-essential systems in a seaway with $\mathrm{H}_S > 17.7\ \mathrm{m}$.

Long-crested irregular seaways were simulated using linear superposition of 20 sinusoidal components to form a unidirectional seaway. Unidirectional seaways tend to be conservative (i.e. they generally represent the worst case) since all the energy flux is flowing in the same direction. Simulated motions vary with seed numbers used to generate the random phases between wave components. However, the variation of motion statistics with input phase seeds is usually very small when the ship does not approach capsize.

For each seaway, simulations were conducted for a matrix of ship speeds and headings:

Table 4: *Seaway Conditions Investigated – Bretschneider Spectra*

Sea State	**Seaway Type**	$\mathbf{H_S}$ **(m)**	$\mathbf{T_P}$ **(s)**	**Notes**
5	Bretschneider	4.0	8.3	T_P = OONA 5%
			15.5	T_P = OONA 95%
6	Bretschneider	6.0	10.3	$T_P \simeq$ OONA 5%
			16.2	T_P = OONA 95%
7	Bretschneider	9.0	13.1	$T_P \simeq$ OONA 5%
			18.5	T_P = OONA 95%
8	Bretschneider	14.0	16.4	$T_P \sim$ OONA 5%
			18.6	T_P = OONA 95%
>8	Bretschneider	17.7	20.0	T_P = OONA 5%
			25.7	T_P = OONA 95%
H_S – Significant Wave Height; T_P – Peak Wave Period;				
OONA – Open Ocean North Atlantic (**ref NATO Sea State Table**)				

Table 5: *Seaway Conditions Investigated – JONSWAP Spectra*

Sea State	**Seaway Type**	$\mathbf{H_S}$ **(m)**	$\mathbf{T_P}$ **(s)**	**Notes**
5	JONSWAP	4.0	8.2	T_P = LECC 5%
			13.6	T_P = LECC95%
6	JONSWAP	6.0	9.3	T_P = LECC5%
			13.6	T_P = LECC95%
7	JONSWAP	9.0	11.0	T_P = LECC5%
			17.1	T_P = LECC95%
H_S – Significant Wave Height; T_P – Peak Wave Period;				
LECC – Littoral East Coast Canada (**ref TDC Wind and Wave Atlas, East Coast of Canada**)				

Ship Speed: 0 to 30 kts in 5 kt increments

Ship Heading: 0 $^\circ$ to 345 $^\circ$ in 15 $^\circ$ increments

For each wave height the corresponding mean wind speed at 19.5 m elevation was assumed to be from the starboard beam (regardless of wave direction) and given by

$$v = 1.823\mathrm{H}_S + 3.45$$

in $\mathrm{m/s}$.

For simulations representing a nominal ship speed, the propeller RPM was set to a value such that FREDYN would give the desired ship speed in calm water. The propeller RPM used to give a desired ship speed with FREDYN will differ from the actual propeller RPM for the HALIFAX class due to assumptions made in numerical modelling.

It should be noted that FREDYN does not model variable pitch propellers, and that the present results are for the HALIFAX propellers set to a specified pitch value.

The program FREDYN requires average wave period, T_{wa}, as an input parameter. The following relationship, based on a Bretschneider spectrum, was used to determine average wave period as a function of a given peak wave period:

$$\mathrm{T}_{wa} = 0.772\mathrm{T}_P$$

The simulation time step was $0.1\ \mathrm{s}$ for all runs, and the duration of each simulation was one hour ($3620\ \mathrm{s}$ including a ramp-up time for eliminating integration start-up transients), which is considered adequate for providing enough motion data for meaningful statistical analysis.

4 Simulation Results

4.1 FREDYN Files

Each seaway has 168 simulation runs (7 speeds x 24 headings) associated with it. Each simulation run results in four files:

- *.inp: a copy of the fredyn.inp file, the structured input file for FREDYN
- *.out: a copy of the fredyn.out file, the structured output file from FREDYN
- *.dat: a copy of the fredyn.dat file, the raw output file from FREDYN

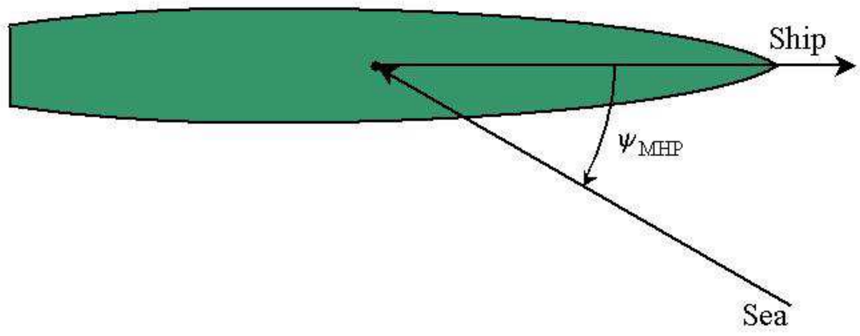

Figure 2: *Reference Direction for Sea in MHP Convention*

- *.acc: a copy of the freacc.dat file, the ship-fixed accelerations of the CG and two other points

All the data files are stored on a 3 DVD set. The *.out file is a printer-friendly version of the *.dat file with a statistical summary appended to the end. The data collected in the file are: Zetag1+2 (wave surface displacement), ALFAy (wave slope), XE, YE, ZE (position of the ship center of gravity with respect to the earth-fixed reference frame), PHI, THETA, PSI (the orientation of the ship with respect to the earth-fixed reference frame), PSI - PSIO (heading relative to initial heading), UG, VG, WG (the velocity of the ship expressed in the ship-fixed reference frame), and P, Q, R (the angular velocity of the ship in the ship-fixed reference frame).

It should be noted that in the FREDYN program, astern seas are considered to have zero relative angle (see Figure 1), which is different from the MHP convention where head seas are considered to be at zero relative angle (see Figure 2). The heading data in the FREDYN output files *.dat and *.out will reflect this astern-sea-as-zero-relative convention. The FREDYN convention is corrected to the MHP convention in the *.csv file in section 4.2 described below.

The *.acc file is the collection of acceleration data: XCOG, YCOG, ZCOG (accelerations of the ship center of gravity expressed in the ship-fixed reference frame), PDOT, QDOT, RDOT (the angular accelerations of the ship expressed in the ship-fixed reference frame), and the accelerations of up to 10 points associated with the ship. In the present case, two points were used: X1, Y1, Z1 (the accelerations at a representative point on the deck in the Hangar: 24.6 m aft of midships (station 10), on the centerline, 11.4 m above the baseline) and X2, Y2, Z2 (the accelerations at a representative point on the Flight Deck: 47.8 m aft of midships (station 10), on the centerline, 11.4 m above the baseline)[2].

[2]Actual securing points may not be on the centerline of the ship. The current proposed securing device allows for variances of ± 0.5 m fore and aft, and ± 0.5 m athwartships. Slightly higher loads

In addition, there may be a fifth file, profan.dat, which is generated when there is a capsize event (roll angle exceeds 90.0 degrees). This file captures the information relative to the capsize. These files are also included on the appropriate DVDs. The following simulation runs in this study resulted in capsize:

- Seaway: JONSWAP H_S = 9.0 m, T_P = 11.0 s; Ship: Speed = 0 kts, Heading = 120°; (file: profanHs9Tp11v0h120.dat on DVD2)
- Seaway: JONSWAP H_S = 9.0 m, T_P = 11.0 s; Ship: Speed = 0 kts, Heading = 135°; (file: profanHs9Tp11v0h135.dat on DVD2)
- Seaway: JONSWAP H_S = 9.0 m, T_P = 11.0 s; Ship: Speed = 0 kts, Heading = 150°; (file: profanHs9Tp11v0h150.dat on DVD2)
- Seaway: JONSWAP H_S = 9.0 m, T_P = 11.0 s; Ship: Speed = 10 kts, Heading = 270°; (file: profanHs9Tp11v10h270.dat on DVD2)
- Seaway: Bretschneider H_S = 14.0 m, T_P = 16.4 s; Ship: Speed = 5 kts, Heading = 240°; (file: profanHs14Tp16v5h240.dat on DVD3)
- Seaway: Bretschneider H_S = 14.0 m, T_P = 16.4 s; Ship: Speed = 30 kts, Heading = 0°; (file: profanHs14Tp16v30h0.dat on DVD3)
- Seaway: Bretschneider H_S = 14.0 m, T_P = 16.4 s; Ship: Speed = 30 kts, Heading = 345°; (file: profanHs14Tp16v30h345.dat on DVD3)
- Seaway: Bretschneider H_S = 17.7 m, T_P = 20.0 s; Ship: Speed = 10 kts, Heading = 180°; (file: profanHs14Tp16v10h180.dat on DVD3)
- Seaway: Bretschneider H_S = 17.7 m, T_P = 20.0 s; Ship: Speed = 10 kts, Heading = 195°; (file: profanHs14Tp16v10h195.dat on DVD3)
- Seaway: Bretschneider H_S = 17.7 m, T_P = 20.0 s; Ship: Speed = 30 kts, Heading = 270°; (file: profanHs14Tp16v30h270.dat on DVD3)

As stated with respect to one of the earlier studies, the choice of random seed number will directly affect the phase difference between the wave components, and will therefore alter the details of the motion at and near capsize. For the purpose of this study, it is only necessary to identify that the ship is at or near capsize conditions; the details of the capsize event are beyond the present scope, and may be investigated at a latter date.

(accelerations) may occur with off-center securing points.

4.2 Post Processing

Additional processing was performed to extract the statistical data (mean value, standard deviation, minimum value and maximum value) for the following parameters:

- Speed;
- Heading (Relative wave heading MHP convention: 0° for head seas; 90° for seas from the starboard beam);
- Heave (position);
- Roll (angle); and
- Pitch (angle).

These parameters are copied from the FREDYN *.out file into the appropriate .csv file (with the heading corrected to MHP convention).

The accelerations (from the *.acc file) at the representative points on the hangar deck (X1, Y1, Z1) and the flight deck (X2, Y2, Z2) are used to calculate force estimates, which are then analyzed statistically, and the results written to the same .csv files. All the accelerations are with respect to the ship-fixed axes, and include gravitational force contributions. These accelerations resulted in:

- Longitudinal (with respect to the ship centerline) acceleration at the hangar
- Lateral (with respect to the ship centerline) acceleration at the hangar
- Vertical acceleration at the hangar
- Generalized longitudinal force estimator at the hangar
- Generalized lateral force estimator at the hangar
- Longitudinal (with respect to the ship centerline) acceleration at the flight deck
- Lateral (with respect to the ship centerline) acceleration at the flight deck
- Vertical acceleration at the flight deck
- Generalized longitudinal force estimator at the flight deck
- Generalized lateral force estimator at the flight deck

The resulting data were captured in a FreHal*seawayName*.csv file, where *seawayName* is the name of the seaway in the format BretHs#Tp# (or JonsHs#Tp#).

Since the helicopter mass can be assumed to be constant, the accelerations at the hangar and flight deck positions are direct "estimates" of the associated forces at these points. Generalized force estimators account for the effects of friction in reducing the required securing loads [8], [9]. To calculate the generalized force estimator, a friction coefficient (μ) was applied to the vertical acceleration (which estimates the normal force) at each point to get a friction force estimator. A value of 0.5 was assumed, but the actual value will depend on surface properties of the helicopter tires and the flight deck. If the friction force estimator was greater than the lateral (or longitudinal) force estimator, no motion would result and the generalized force estimate was set to zero. If the lateral (longitudinal) force estimator was greater than the friction force estimator, the generalized force estimate was set to the difference between the lateral (longitudinal) and friction force estimators, with the direction (+ or -) dependent on the direction of the original lateral (longitudinal) forces estimator.

$$LatGFE = \begin{cases} 0 & |LatFE| < \mu VertFE \\ sign\left(LatFE\right)\left|LatFE - \mu VertFE\right| & |LatFE| > \mu VertFE \end{cases}$$

4.3 Results Plots

In all the simulations, the wind is from the starboard beam, and is proportional to the significant wave height.

Polar plots of the maximum roll with respect to ship's speed and heading in each seaway can be found in Annexes A and B. Polar plots of the maximum estimate of lateral force at the hangar deck with respect to ship's speed and heading in each seaway can be found in Annexes C and D. A complete set of polar plots for roll and pitch angles, as well as all force estimators at the flight deck and hangar deck locations are included with the tabulated data in the companion memorandum [3].

The polar plots can be read intuitively by imagining oneself on the ship facing the bow (top of plot) with the port to the left. Each of the radial lines represents the relative direction of the incoming seaway. The radial lines are shown for 30° increments on the polar plots, with 90° to the starboard and 270° to the port. The rings in the plots represent (less intuitively) the ships speed in 10 knot increments. The plots are colour coded such that blue represents a low magnitude of the parameter being plotted, and red represents a high value.

The plots indicate that for open-ocean (Bretschneider spectrum) course-keeping, the most severe roll occurs in waves with significant wave height of $14\,\mathrm{m}$ and a peak period of 16.4 seconds. In particular, the simulation results indicate that following

seas are conducive to roll, and may present a risk of capsize at high speed (30 knots). Seas from the port bow quarter can also result in high roll angles when the ship is travelling at 5 to 10 knots. High lateral accelerations also occur at 10 knots in port beam and port stern-quartering seas for this wave height and period. The results also indicate high lateral accelerations at 20 knots in a starboard beam sea.

The only other open-ocean seaway to induce high roll angles was that with $H_S = 17.7\,\mathrm{m}$ and $T_P = 20.0\,\mathrm{s}$, where head seas at 5 to 10 knots, and seas from the port beam at 30 knots resulted in high roll angles, but no capsize event was detected. There were also high roll angle and high lateral accelerations in seas from just forward of the starboard beamwhen the ship was at 25 knots.

For the littoral water (JONSWAP spectrum) simulations, the only seaway with high roll was that with $H_S = 9.0\,\mathrm{m}$ and $T_P = 11.0\,\mathrm{s}$, where seas from the port beam can result in high lateral accelerations at ship speeds between 5 and 25 knots, and high roll angles and a risk of capsize at 10 knots. Seas from the starboard beam also lead to increased roll angles and lateral accelerations, but to a lesser extent. When the ship is at 0 knots, seas from the starboard bow quarter can induce high roll angles and a risk of capsize.

5 Conclusions

A comprehensive study was carried out to define the motion characteristics of the HALIFAX class in a broad variety of sea states. The results provide data for determining the loads induced on helicopter securing arrangements by the moving ship. The results have been presented in the form of polar plots relating the maximum roll angle experienced by the ship and the maximum lateral force estimate at the hangar deck to the relative sea direction and ship's speed. As expected, in severe sea conditions, there are higher maximum roll angles and higher lateral forces at the hangar deck.

In all the simulations, the wind is from the starboard beam, and is proportional to the significant wave height. The results show that the wind affects the motion parameters, as the highest roll angles and lateral forces were usually experienced when the sea was from the port beam.

The motions in extreme conditions will be important factors in the design of helicopter securing methods, equipment, and procedures.

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4. J. O. De Kat, H. R. Luth, E. F. G. Van Daalen, and A. P. Van’t Veer. FREDYN: A Computer Program for the Simulation of a Steered Ship in Extreme Seas and Wind. Theory Manual, Version 8.0. MARIN, 1999.

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6 Symbols

Table 6: *General Symbols*

Symbol	Description
ϕ, θ, ψ	Roll, Pitch, Yaw (heading) angle respectively
ψ_{FREDYN}	Yaw angle of ship with respect to sea direction - FREDYN convention
ψ_{MHP}	Sea direction with respect to ship - MHP convention
$\triangle$	Displacement
μ	Coefficient of friction
t_s	Trim by stern
x_e, y_e, z_e	earth-fixed axes
x_g, y_g, z_g	ship-fixed axes (fixed at CG)
B	Beam
$\overline{GM}_{fluid}$	Metacentric height, corrected for free surface
H_S	Significant wave height
$\overline{KG}$	Vertical centre of gravity above baseline
L	Length between perpendiculars
$\overline{LCG}$	Longitudinal centre of gravity, aft of midships
T_{3f}, T_{3v}	Coordinate transformation from earth-fixed reference frame to ship-fixed ref. frame for translational and rotational velocities respectively
T_{mid}	Midships draft
T_P	Peak wave period

Table 7: *FREDYN Symbols*

Symbol	Description
ALFAY	Beamwise component of wave slope at ship CG
DEL(1)	Rudder angle
P, Q, R	Roll, pitch, yaw velocities about x_g, y_g, z_g resp.
PDOT, QDOT, RDOT	Roll, pitch, yaw accelerations about x_g, y_g, z_g resp.
PHI, THETA, PSI	Roll, pitch, yaw (heading) angles
PSI - PSI0	Ship heading relative to initial heading
T	Time relative to beginning of simulation
UG, VG, WG	Speed of ship CG in direction x_g, y_g, z_g resp.
X1, Y1, Z1, X2, Y2, Z2	Accel. of 1^{st}, 2^{nd} pts. on ship, parallel to x_g, y_g, z_g resp.
XCOG, YCOG, ZCOG	Accel. of ship CG in direction x_g, y_g, z_g resp.
XE, YE, ZE	Displacement of ship CG along x_e, y_e, z_e resp.
ZETAG	Wave elevation at ship CG

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Annex A
Polar Plots of Maximum Absolute Roll Angle – Bretschneider Spectra (Open Ocean)

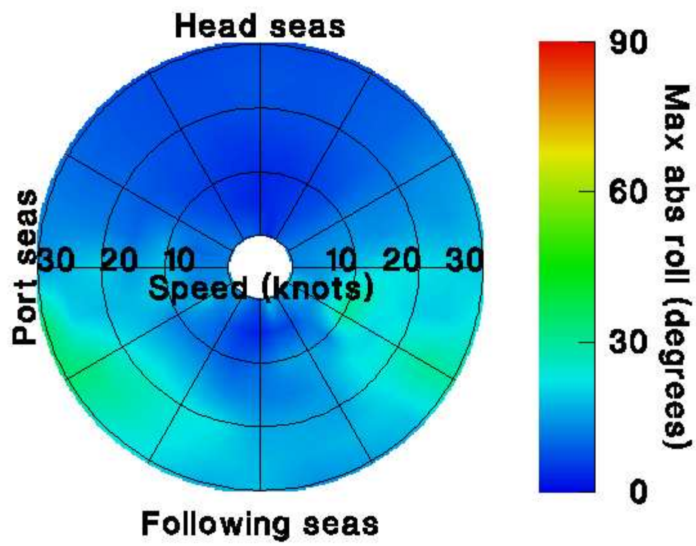

Figure A.1: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 4.0$ m *and* $T_P = 8.3$ s*.*

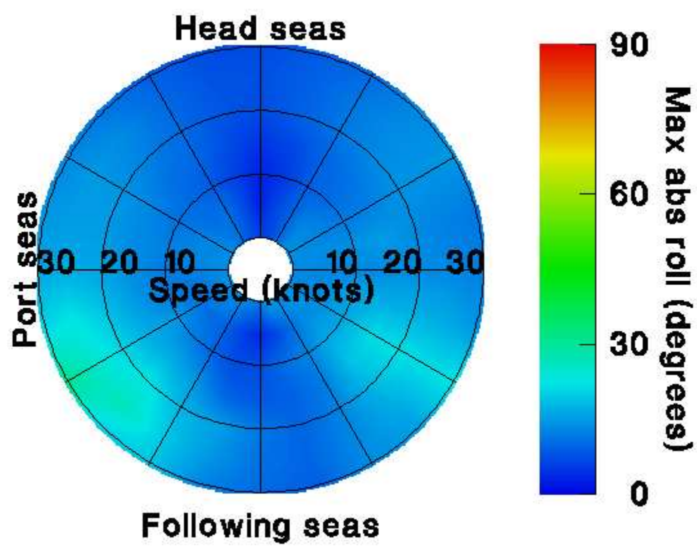

Figure A.2: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 4.0$ m *and* $T_P = 15.5$ s*.*

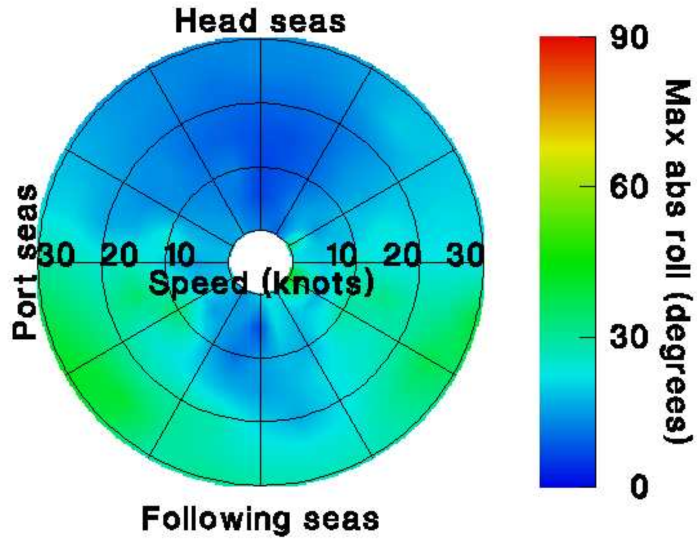

Figure A.3: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 6.0\ \mathrm{m}$ *and* $T_P = 10.3\ \mathrm{s}$*.*

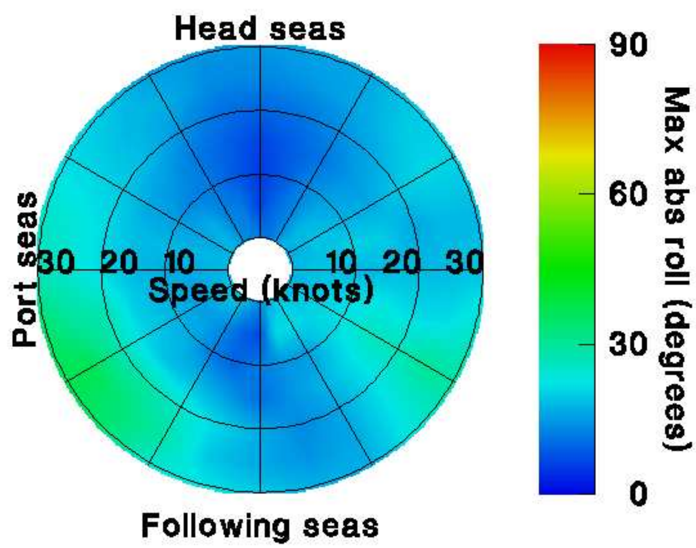

Figure A.4: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 6.0\ \mathrm{m}$ *and* $T_P = 16.2\ \mathrm{s}$*.*

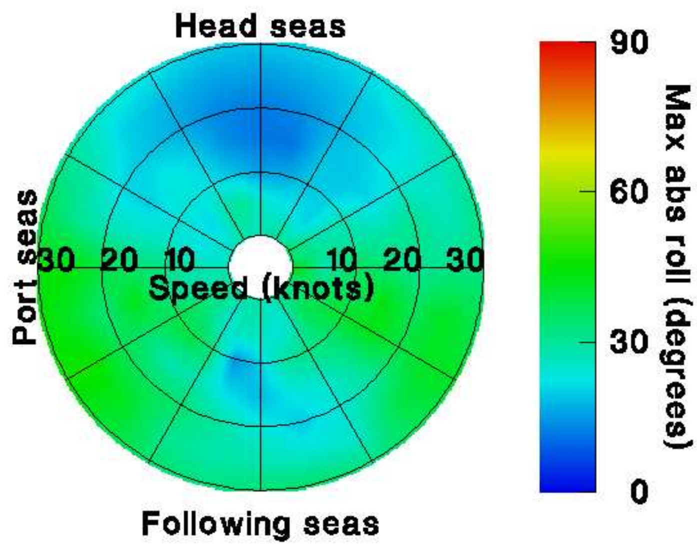

Figure A.5: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 9.0\ \mathrm{m}$ *and* $T_P = 13.1\ \mathrm{s}$*.*

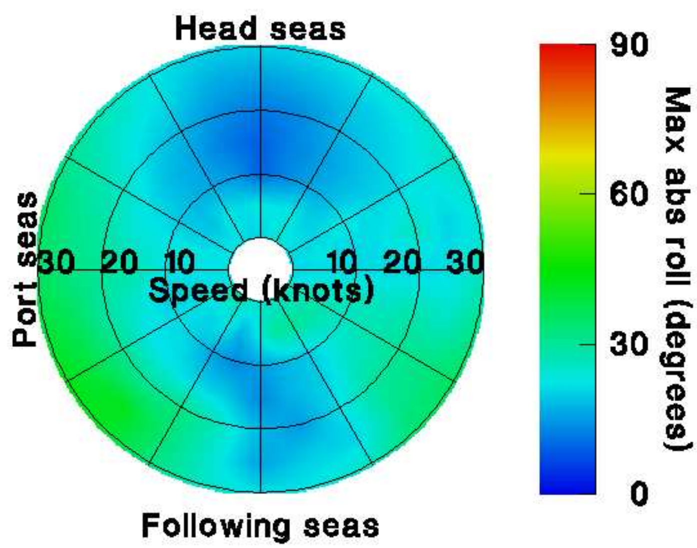

Figure A.6: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 9.0\ \mathrm{m}$ *and* $T_P = 18.5\ \mathrm{s}$*.*

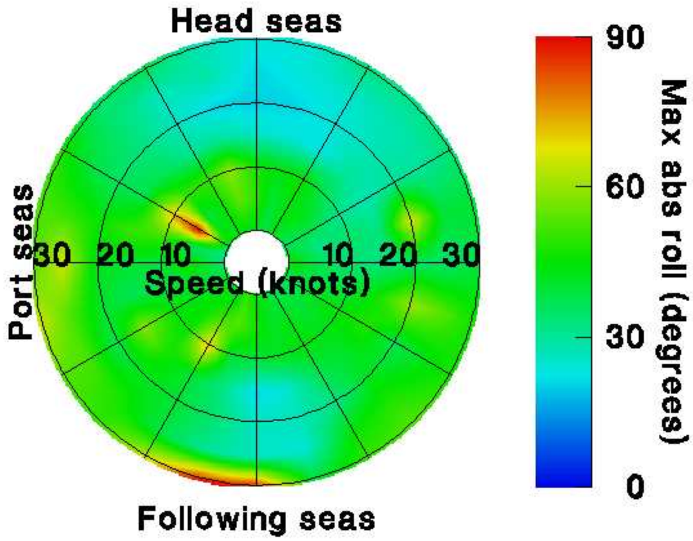

Figure A.7: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 14.0$ m *and* $T_P = 16.4$ s*.*

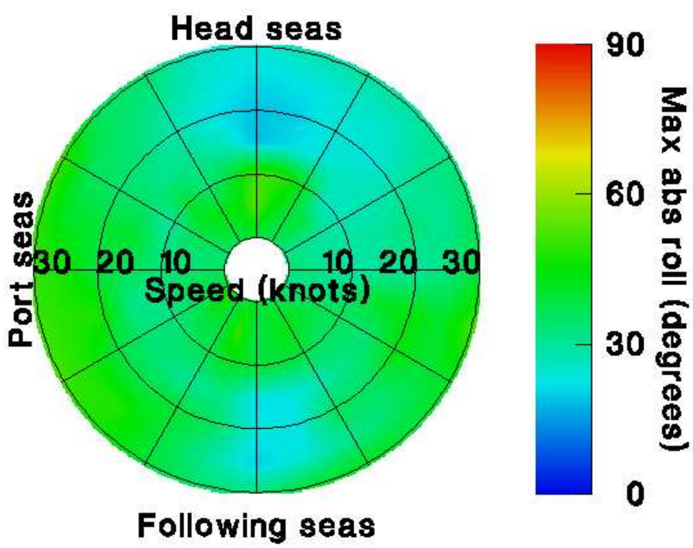

Figure A.8: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 14.0$ m *and* $T_P = 18.6$ s*.*

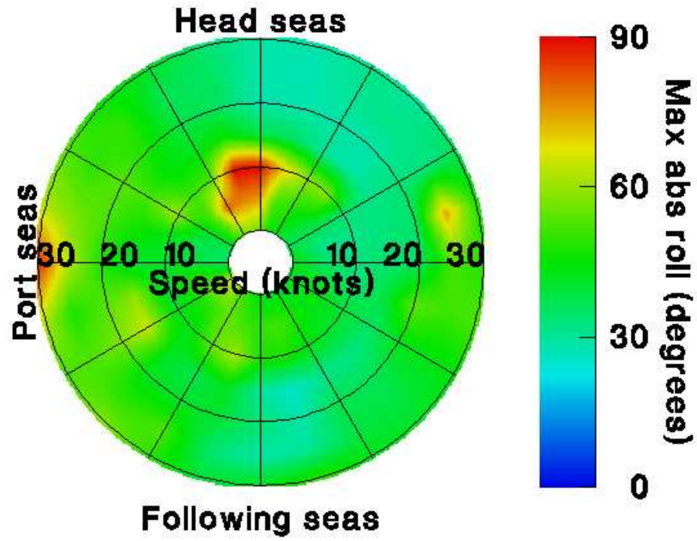

Figure A.9: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 17.7\ \mathrm{m}$ *and* $T_P = 20.0\ \mathrm{s}$*.*

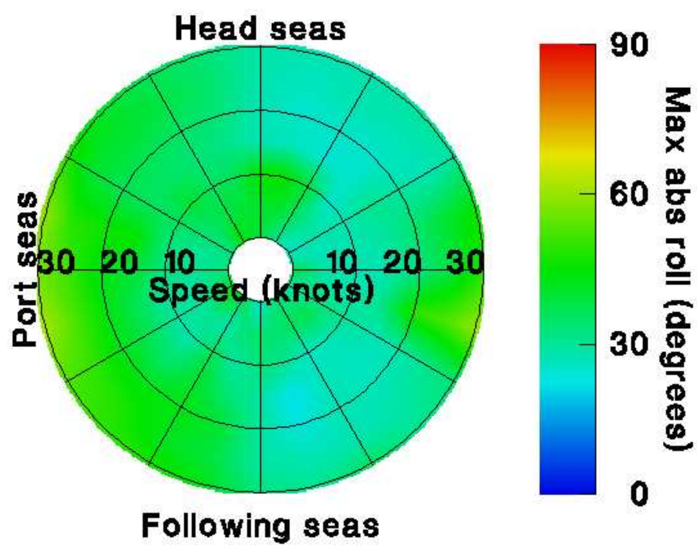

Figure A.10: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 17.7\ \mathrm{m}$ *and* $T_P = 25.7\ \mathrm{s}$*.*

Annex B
Polar Plots of Maximum Absolute Roll Angle – JONSWAP Spectra (Coastal Waters)

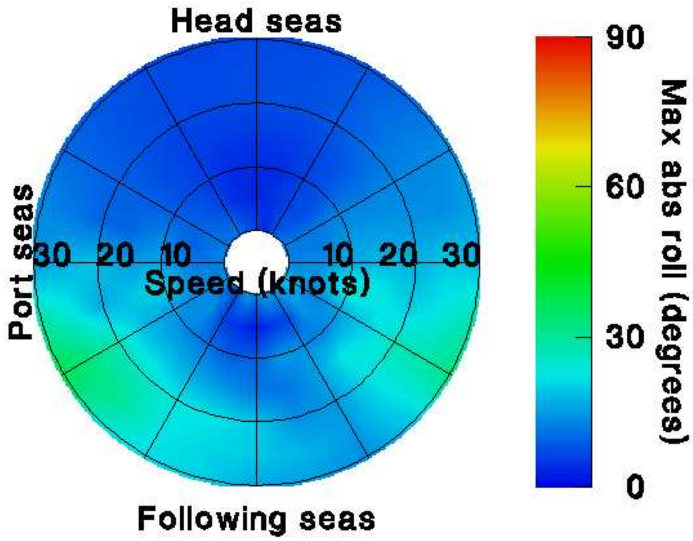

Figure B.1: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 4.0$ m *and* $T_P = 8.2$ s.

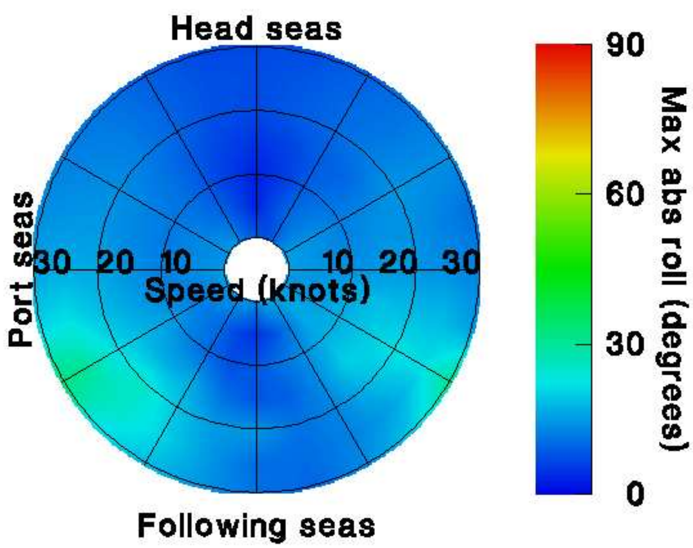

Figure B.2: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 4.0$ m *and* $T_P = 13.6$ s.

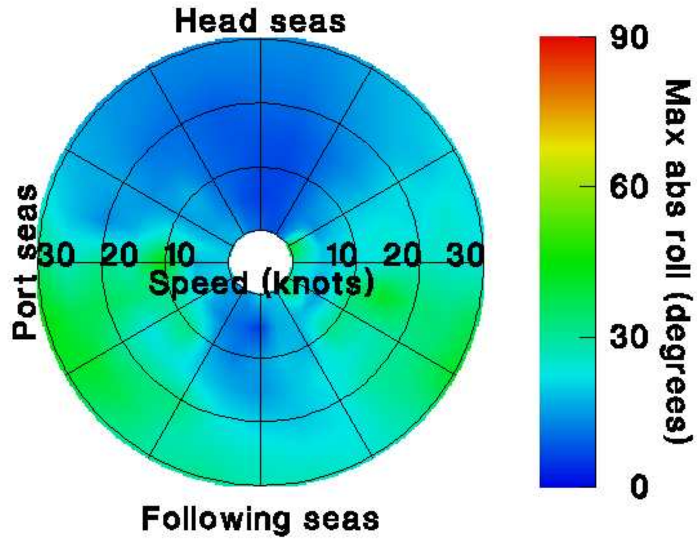

Figure B.3: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 6.0\ \mathrm{m}$ *and* $T_P = 9.3\ \mathrm{s}$.

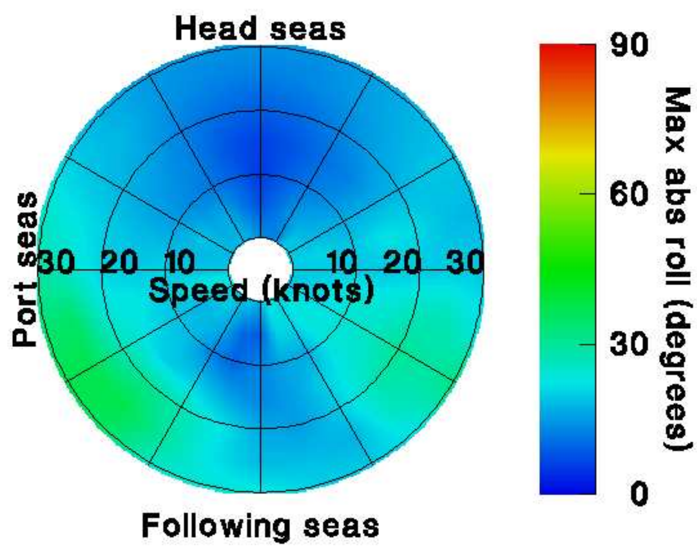

Figure B.4: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 6.0\ \mathrm{m}$ *and* $T_P = 13.6\ \mathrm{s}$.

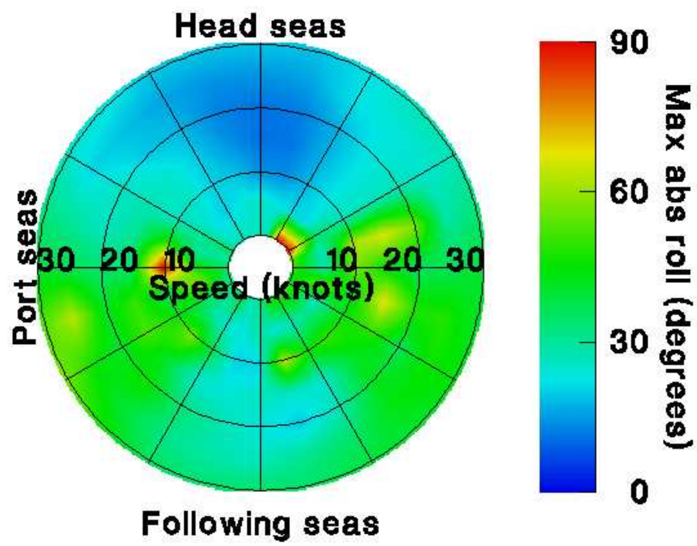

Figure B.5: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 9.0$ m *and* $T_P = 11.0$ s.

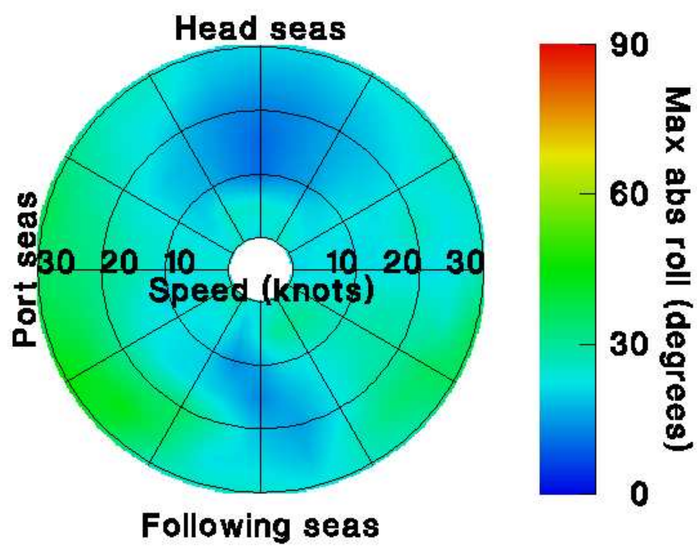

Figure B.6: *Max. Abs. Roll Angles with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 9.0$ m *and* $T_P = 17.1$ s.

Annex C
Polar Plots of Maximum Absolute Lateral Force Estimator at Hangar Deck – Bretschneider Spectra (Open Ocean)

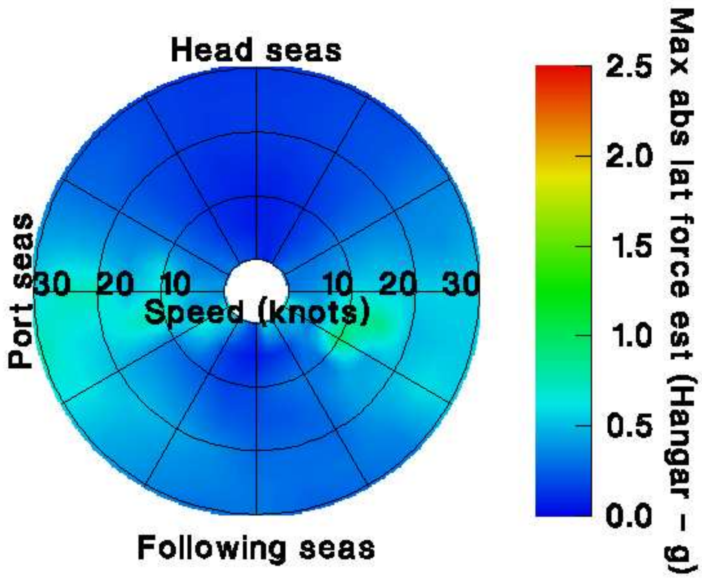

Figure C.1: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 4.0$ m *and* $T_P = 8.3$ s.

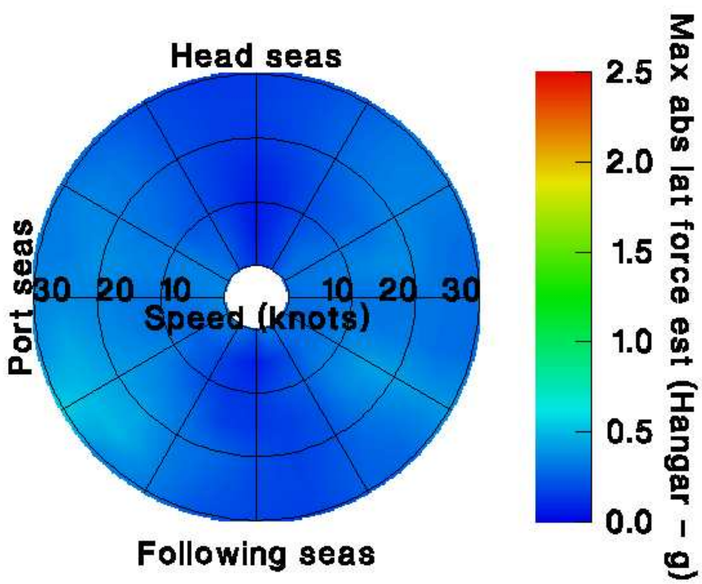

Figure C.2: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 4.0$ m *and* $T_P = 15.5$ s.

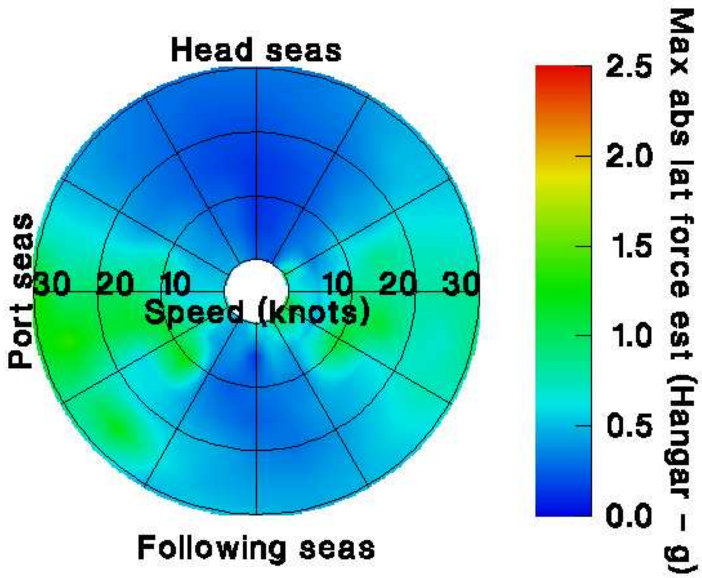

Figure C.3: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 6.0$ m *and* $T_P = 10.3$ s.

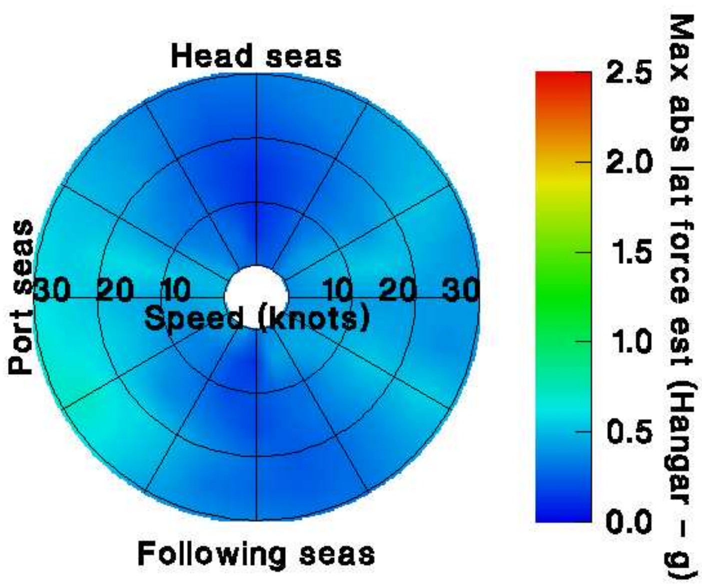

Figure C.4: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 6.0$ m *and* $T_P = 16.2$ s.

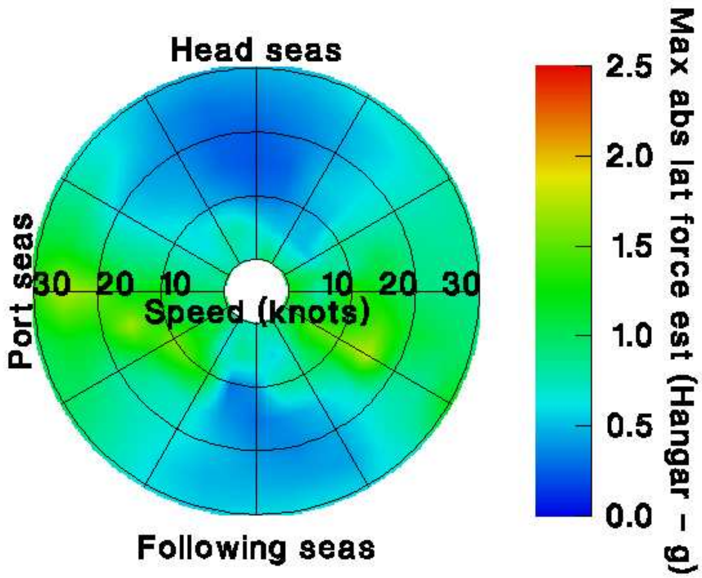

Figure C.5: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 9.0$ m *and* $T_P = 13.1$ s.

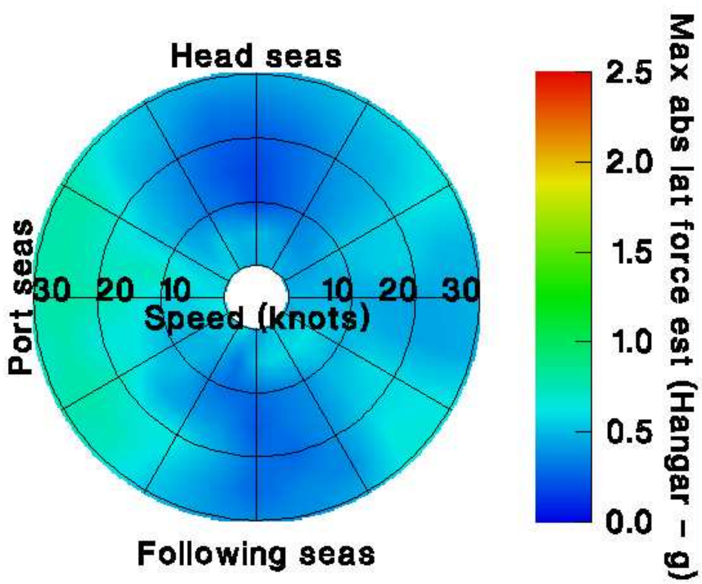

Figure C.6: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 9.0$ m *and* $T_P = 18.5$ s.

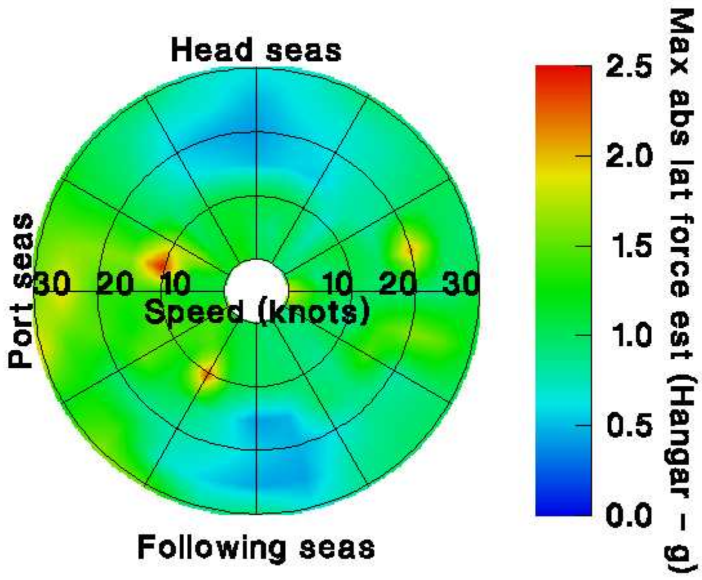

Figure C.7: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 14.0$ m *and* $T_P = 16.4$ s*.*

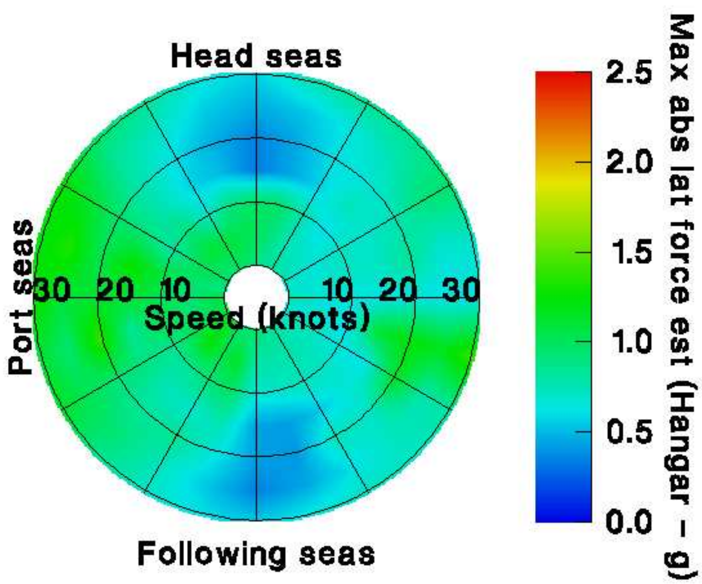

Figure C.8: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 14.0$ m *and* $T_P = 18.6$ s*.*

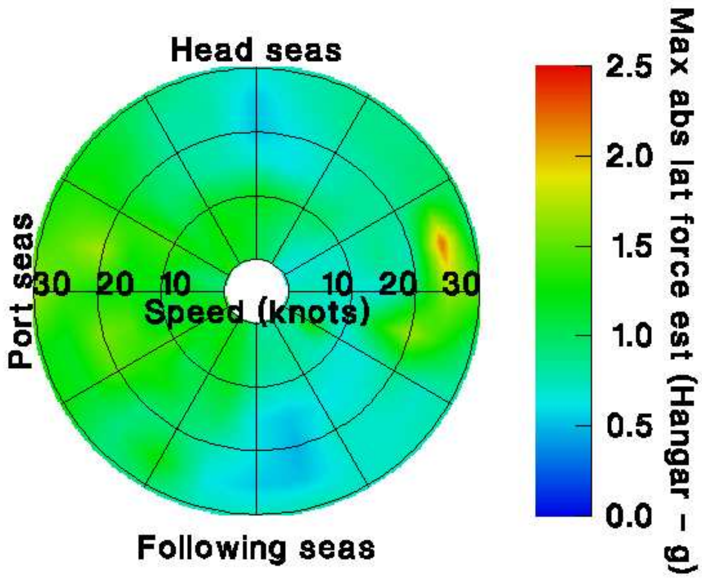

Figure C.9: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 17.7$ m *and* $T_P = 20.0$ s*.*

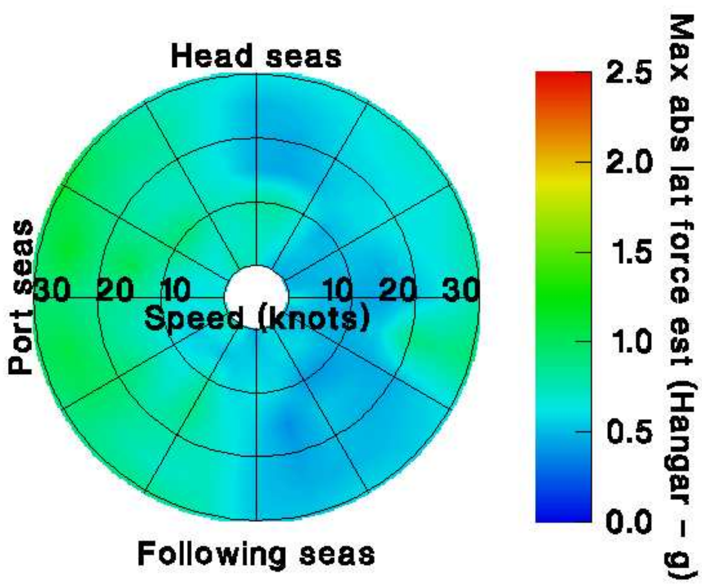

Figure C.10: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: Bretschneider with* $H_S = 17.7$ m *and* $T_P = 25.7$ s*.*

Annex D
Polar Plots of Maximum Absolute Lateral Force Estimator at Hangar Deck – JONSWAP Spectra (Coastal Waters)

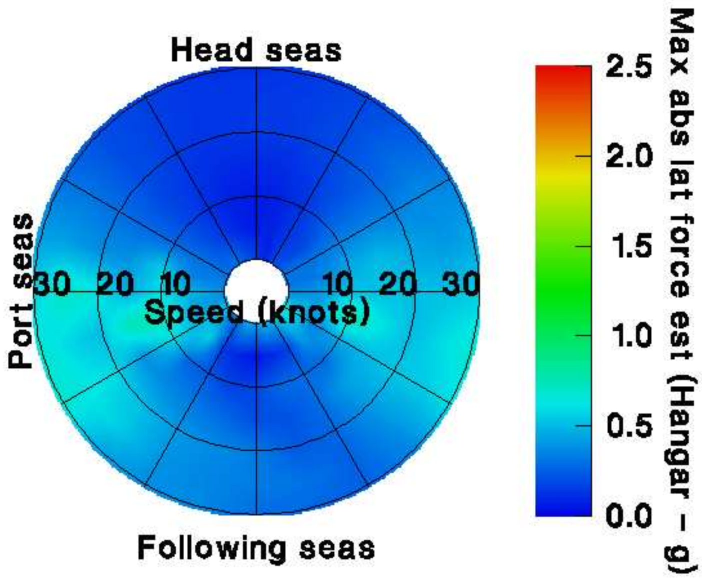

Figure D.1: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 4.0$ m *and* $T_P = 8.2$ s.

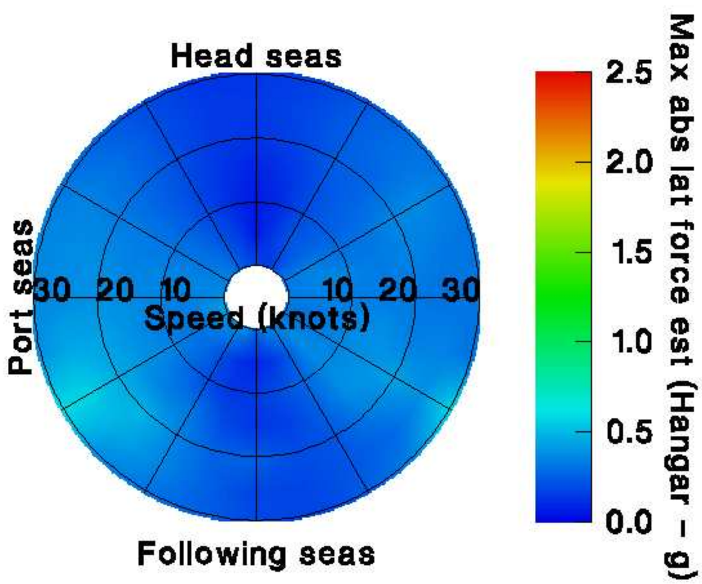

Figure D.2: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 4.0$ m *and* $T_P = 13.6$ s.

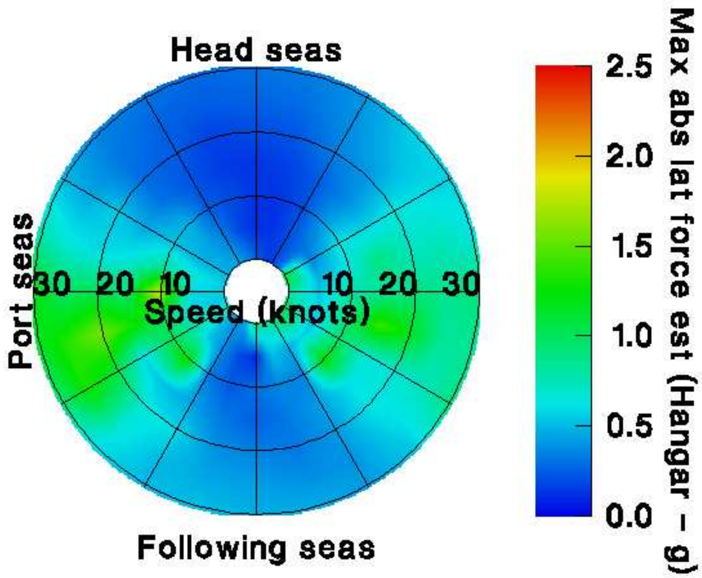

Figure D.3: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 6.0$ m *and* $T_P = 9.3$ s*.*

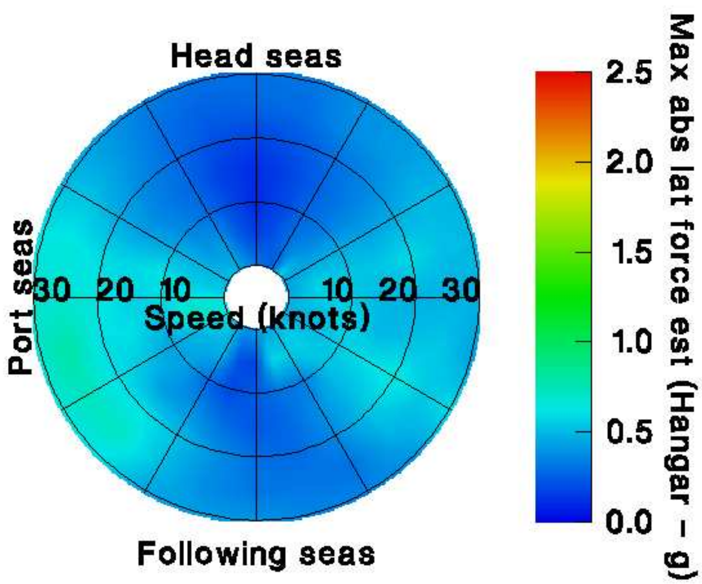

Figure D.4: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 6.0$ m *and* $T_P = 13.6$ s*.*

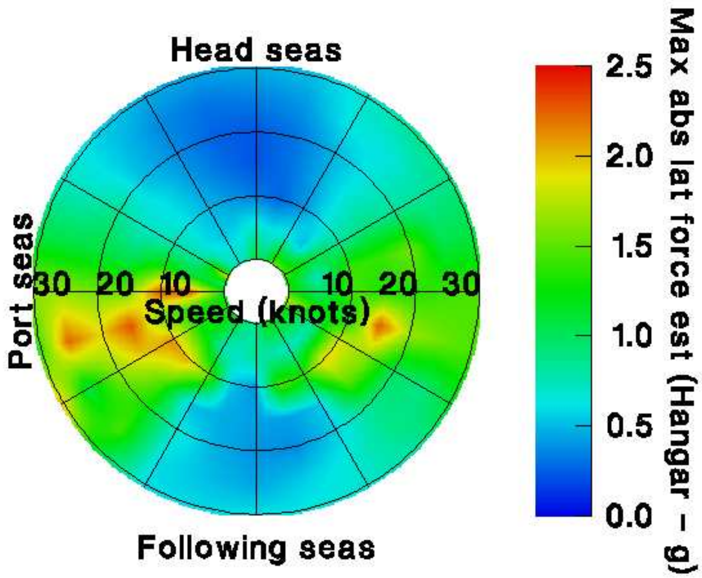

Figure D.5: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 9.0$ m *and* $T_P = 11.0$ s*.*

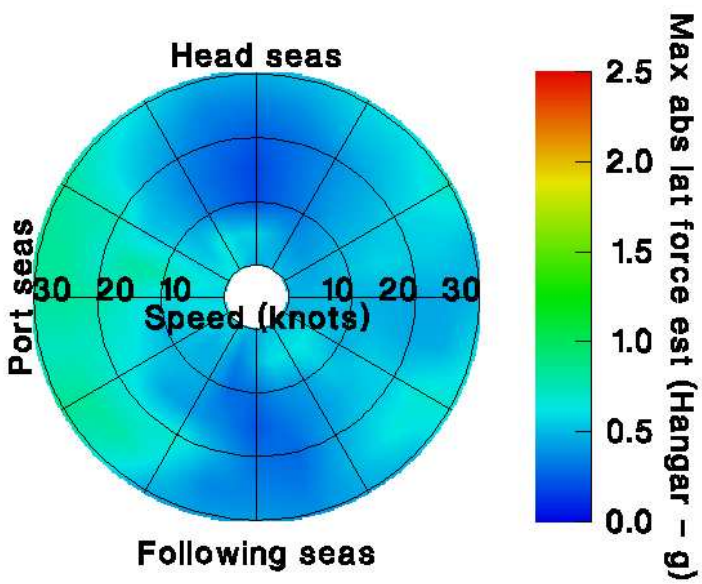

Figure D.6: *Max. Abs. Lat. Force Est. at the Hangar Deck with respect to Speed and Heading in a Seaway: JONSWAP with* $H_S = 9.0$ m *and* $T_P = 17.1$ s*.*

Annex E
NATO Sea State Table

Table E.1: *NATO Sea State Table (After Table D-1 in NATO STANAG 4194)*

Sea State Number	Significant Wave Height (m)		Sustained Wind Speed (Knots)*		% Prob. of Sea State	Wave Period (s)	
	Range	Mean	Range	Mean		Range†	Most Prob.‡
0 - 1	0.00 - 0.10	0.05	0 - 6	3.0	0.70	—	—
2	0.10 - 0.50	0.30	7 - 10	8.5	6.80	3.3 - 12.8	7.5
3	0.50 - 1.25	0.88	11 - 16	13.5	23.70	5.0 - 14.8	7.5
4	1.25 - 2.50	1.88	17 - 21	19.0	27.80	6.1 - 15.2	8.8
5	2.50 - 4.00	3.25	22 - 27	24.5	20.64	8.3 - 15.5	9.7
6	4.00 - 6.00	5.00	28 - 47	37.5	13.15	9.8 - 16.2	12.4
7	6.00 - 9.00	7.50	48 - 55	51.5	6.05	11.8 - 18.5	15.0
8	9.00 - 14.00	11.50	56 - 63	59.5	1.11	14.2 - 18.6	16.4
> 8	> 14.00	> 14.00	> 63	> 63.0	0.05	15.7 - 23.7	20.0

*Ambient wind sustained at 19.5 m above surface to generate fully-developed seas. To convert to another altitude, H_2 , apply $V_2 = V_1\,(H_2/19.5)^{1/7}$

†Min. is 5 percentile and max. is 95 percentile for periods give wave height range.

‡Based on periods associated with central frequencies incl. in Hindcast Climatology.

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